THE ROLE OF THE CONCEPTUAL HYDROGEOLOGIC MODEL IN SITE CHARACTERIZATION AND DYNAMIC RISK ASSESSMENT

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ABSTRACT

A fundamental aspect of the Expedited Site Characterization (ESC) methodology developed by Argonne National Laboratory is the use of a dynamic conceptual hydrogeologic model to guide site investigations. A preliminary conceptual model is progressively tested and refined as additional data are integrated to yield a more detailed understanding of the physiographic, geologic, hydrologic, and geochemical processes that together control groundwater flow and contaminant migration within the aquifer system. As the conceptual model evolves, the characterization program is tailored to address the specific data needs identified at each stage of the site investigation. Through this approach, technically defensible, process-oriented hydrogeologic and, if necessary, mathematical site models are developed to facilitate the dynamic analysis of risks arising from the distribution, fate, and transport of contaminants at the investigation site.

An overview of site characterization studies conducted for the hazardous waste contamination site in Bruno, Nebraska, is presented to illustrate Argonne's use of this approach in the investigation of a relatively complex groundwater flow and contaminant transport system and in the evaluation of risk. An extended monitoring program was implemented during the characterization of this site, in order to address critical uncertainties in the hydrogeologic factors controlling long-term groundwater flow and contaminant migration. The final conceptual and mathematical site models provided justification for the definition a hypothetical, downgradient residential location as the primary observation point for a risk-based evaluation of remedial alternatives, using Argonne's dynamic risk assessment approach.

INTRODUCTION

The site characterization methodology developed by Argonne National Laboratory serves as the technical basis for the Standard Provisional Guide for Expedited Site Characterization of Hazardous Waste Contaminated Sites (ASTM 1997). A central theme of the ESC approach is the use of a conceptual hydrogeologic model throughout the site investigation process, as a framework for the selection of appropriate characterization techniques and for the integration and interpretation of site data. Information obtained from the site is used to test and refine the conceptual hydrogeologic model in an iterative process, so that subsequent investigations can be effectively targeted to address critical data needs. Through this approach, technically defensible, process-oriented conceptual and, if necessary, mathematical site models are developed to support the evaluation of risks associated with contaminant fate and transport at the investigation site. To demonstrate Argonne's approach to the use of conceptual hydrogeologic models in site

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characterization and dynamic risk assessment, an overview of studies conducted by Argonne for the hazardous waste site in Bruno, Nebraska, is presented.

BACKGROUND

Bruno is a small (population 150) agricultural community located approximately 50 mi west of Omaha in Butler County, Nebraska, that was the site of a grain storage facility operated by the Commodity Credit Corporation of the U.S. Department of Agriculture (CCC/USDA) in the 1950s and 1960s. During this period, fumigants containing carbon tetrachloride and carbon disulfide were commonly used within the commercial grain storage industry and by the CCC/USDA for treating grain in storage. Since the mid 1960s, grain storage facilities have been operated at the Bruno site by a number of private and commercial organizations.

All Bruno residents receive their domestic water supply from a municipal groundwater distribution system. Prior to 1990, the municipal system was served by two wells (36-1 and 65-1) located within the limits of the village, as shown in Figure 1. In 1984, routine screening for volatile organic compounds (VOCs) by the Nebraska Department of Health (NDH) identified carbon tetrachloride and chloroform in water from the Bruno municipal system. Follow-up analyses by the NDH and the Region VII U.S. Environmental Protection Agency (EPA) confirmed the presence of carbon tetrachloride and chloroform in the public supply wells at concentrations at or above the maximum contaminant levels for these compounds. The CCC/USDA was identified as one of several potentially responsible parties at the Bruno site. In 1990, the contaminated municipal wells were abandoned and replaced by two new wells, located approximately 1 mi west of the town, that are free of VOCs.

In 1993 the CCC/USDA, working under an interagency agreement with the U.S. Department of Energy, requested Argonne to perform an investigation of the groundwater system at Bruno by using Argonne's QuickSite^{SM} ESC methodology. Bruno was subsequently listed on the CERCLA National Priorities List (NPL) by the Region VII EPA.

PRELIMINARY HYDROGEOLOGIC MODEL

For use in the formulation of a preliminary conceptual hydrogeologic model for the Bruno area, geologic, hydrogeologic, groundwater geochemical, and basic climatic data of good quality (but of fairly regional scope) were obtained primarily from studies conducted in Butler County by the Nebraska Water Survey (NWS) (Ginsberg 1983). These data were supplemented by geologic logs available for a very limited number of water wells and test borings in the more immediate vicinity of the village. The topographic and physical characteristics of the site were determined from U.S. Geological Survey mapping (USGS 1968) of the Bruno area, from several aerial photos taken during the period of CCC/USDA operations at the site, and from Argonne staff visits to the site and discussions with residents of the community.

The preliminary conceptual model assembled for the Bruno hydrogeologic system is illustrated in Figures 2 and 3. Bruno lies within an area of rolling hills, bluffs, ridges, and narrow, deeply incised creek valleys developed in the thick Pleistocene loess that blankets the southeastern third of Butler County. The village is sited on the relatively steep southeastern flank

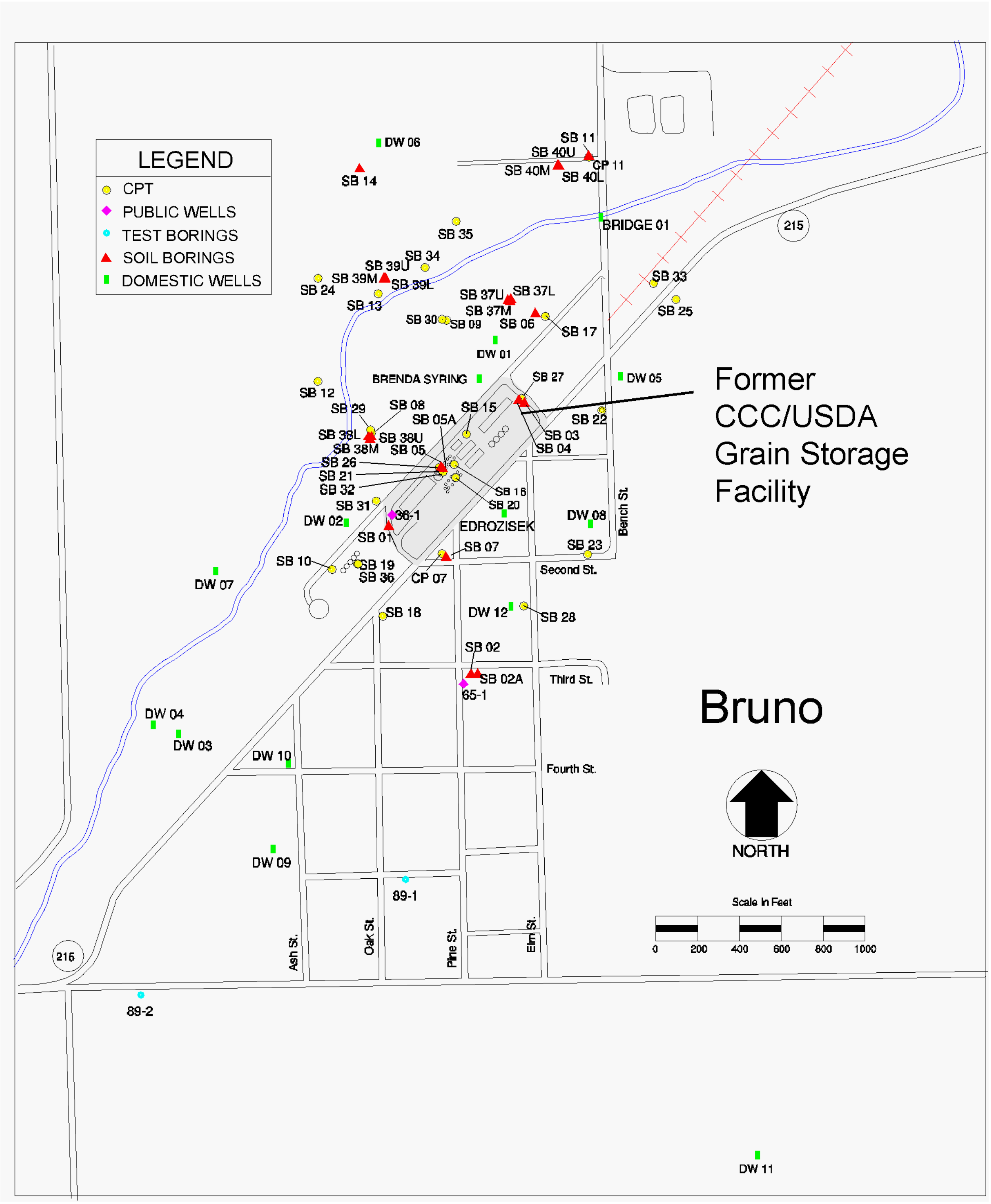

FIGURE 1 Map Showing Locations of All QuickSite[SM] Phase I, Phase II, and Extended Monitoring Activities

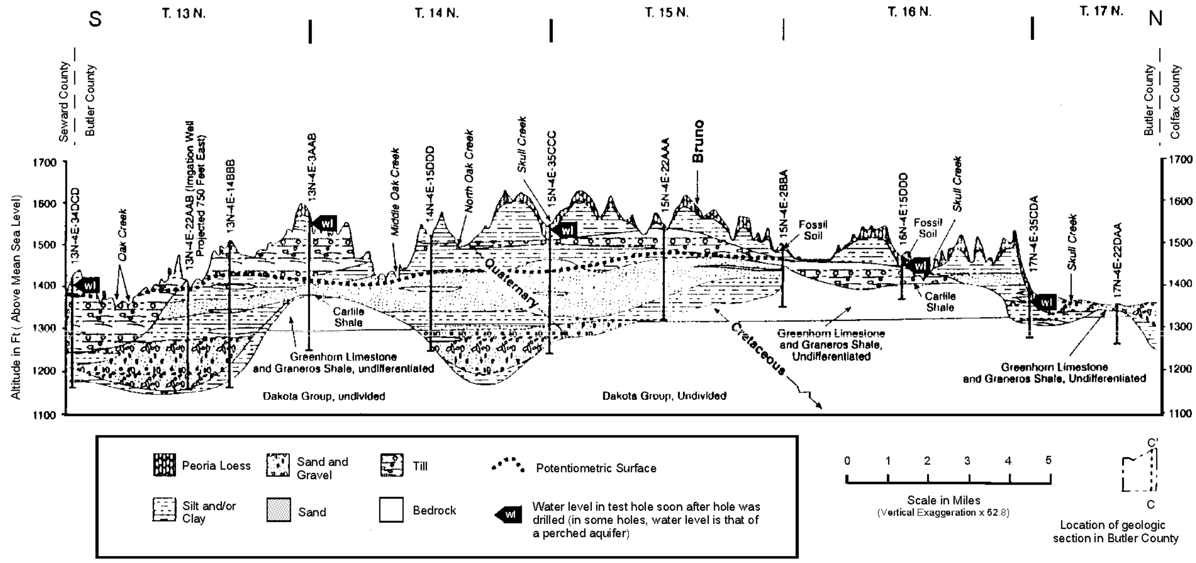

FIGURE 2 South-North Geologic Section through the Eastern Part of Butler County, Nebraska (Source: Ginsberg 1983)

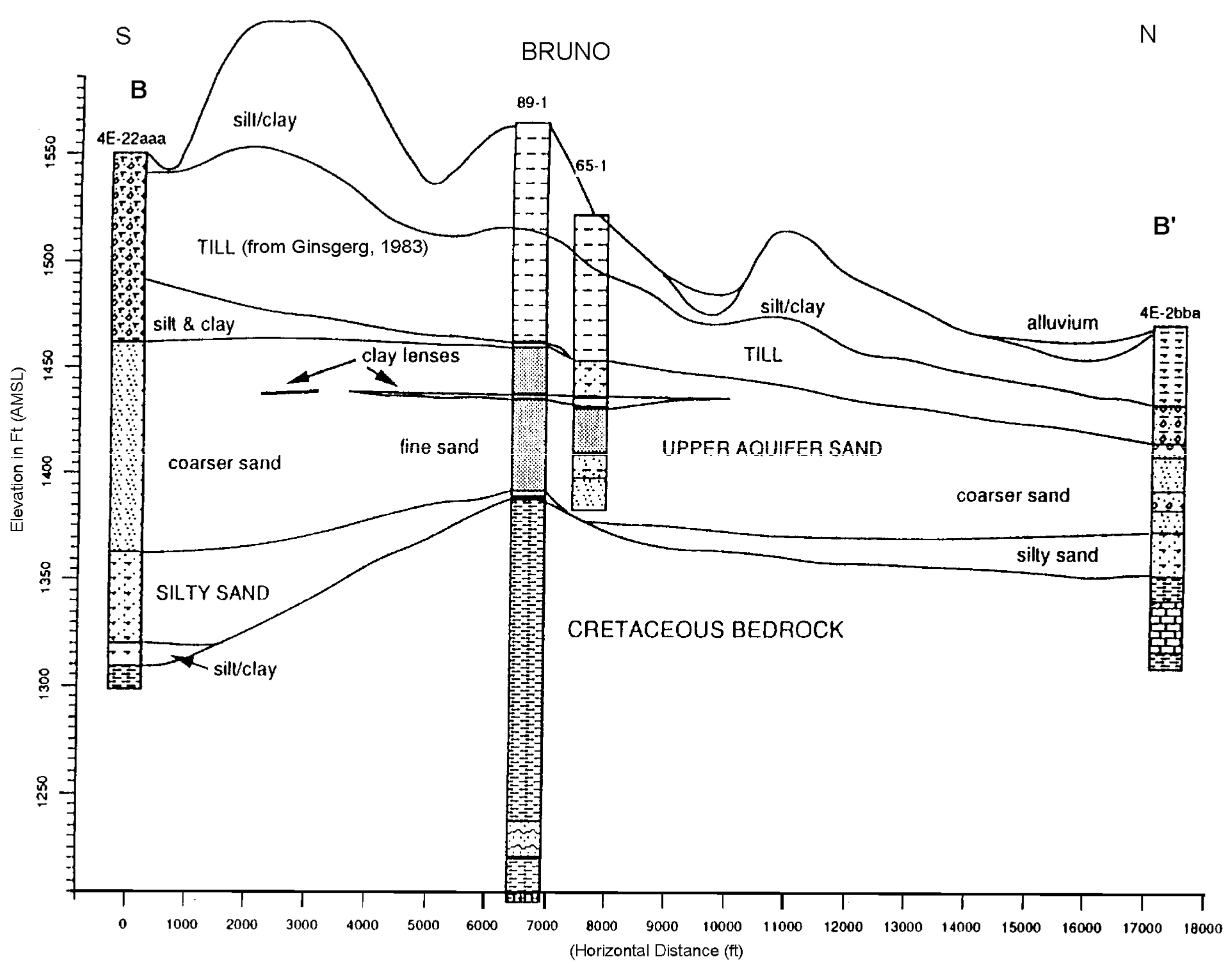

FIGURE 3 South-North Geologic Cross Section through Bruno, Nebraska

of one such northeastward-draining ephemeral creek, in which water levels rise 10 ft or more in response to heavy rains.

The general geologic and hydrogeologic setting of the Bruno area is represented in a south-north cross section (Figure 2) lying approximately 1 mi east of the village. The surficial loess overlies a variable sequence of glacial till and proglacial to glaciofluvial silts, sands, or sands and gravels deposited over an irregular Cretaceous bedrock surface. These Pleistocene deposits form the only groundwater reservoir of significance in eastern Butler County. The regional cross section suggests that the Pleistocene deposits thin northward and are absent 2-3 mi north and northwest of the village. Bedrock units in the vicinity of Bruno consist of relatively impermeable limestones and shales. Regional mapping of an average potentiometric surface for the Pleistocene aquifer sequence, based on sparse well control, suggested a general northwestward direction of groundwater flow across the Bruno area.

Drillers' logs were available for only three borings located within roughly 0.5 mi of Bruno, precluding the development of a detailed local geologic or hydrogeologic picture for the site. A north-south cross section tying two of these wells to two wells in the regional section (Figure 2) is shown in Figure 3. The logs for these wells suggest the local presence of a bedrock high beneath the town, as well as a possible clay aquitard within the relatively flat-lying sandy aquifer unit, overlain by till and surficial loess. No groundwater levels or flow data for wells in the town were available. Information on the distribution of VOC contaminants within the aquifer system was limited to the results obtained for the public water supply wells by the NDH and the EPA, described above.

PHASE I AND PHASE II STUDIES

A phased program of field investigations was conducted at the Bruno site, in order to develop the conceptual model of groundwater flow and contaminant transport within the aquifer system. Phase I of the Bruno ESC study focused primarily on defining the local stratigraphy, hydrostratigraphy, and patterns of groundwater movement at the site. Information obtained from the Phase I studies was used to guide detailed groundwater sampling and supplemental hydrogeologic studies during Phase II of the investigations.

Six conventional borings were drilled to provide a detailed record of lithologic variations within the Pleistocene sequence (see Figure 1). Boring SB01D and portions of borings SB02 and SB03 were continuously cored, and all borings were logged geologically and geophysically. All additional activities at the site were performed by using an electronic cone penetrometer (ECPT) variably equipped with soil sampling, groundwater sampling, or physical and geophysical logging probes. Experimental calibration of the ECPT log responses was first performed adjacent to the continuously cored borings, to verify that the mechanical and geophysical profiles obtained with the ECPT probe could be used as a tool for correlation of the main lithologic intervals identified from the geologic logs and for the selection of sampling intervals at uncored locations. Groundwater sampling was performed at selected depths by using the HydroPunch II during the drilling of the conventional boreholes, as well as with the ECPT, to develop vertical profiles of the variations in groundwater geochemistry and contaminant distribution within the aquifer system. The six conventional borings were completed as temporary well pairs screened in the upper and lower portions of the aquifer system (see below), to permit the periodic determination of groundwater levels and flow directions during the investigations. A single piezometer (SB25) was also installed in the upper portion of the aquifer to extend the water level observation network in this aquifer interval. Aquifer tests were conducted by pumping of the former public water supply wells 36-1 and 65-1, two temporary wells in the lower portion of the aquifer, and one temporary well in the upper portion, to estimate the hydraulic properties of the aquifer materials.

REVISION OF THE PRELIMINARY CONCEPTUAL MODEL

The ESC hydrogeologic investigations confirmed the surficial silt/loess; Cretaceous bedrock; and generally flat-lying, predominantly sandy units predicted from the preliminary hydrogeologic model; however, no distinct glacial tills (as suggested from previous drillers' logs) were identified within the study area. A persistent intermediate layer of clay was also not identified; a finer-grained zone of variable thickness and lithology, consisting of silts, silty sands, and clayey silts, was penetrated in most borings, separating the sandy unit into upper and lower zones.

The ECPT logs and boring data were used to map the distribution and thicknesses of the upper and lower sandy zones and the intermediate silty unit, as shown in Figure 4. The subsurface topography on the upper surfaces of the upper sandy zone and the silty unit, in particular, roughly mirrored the modern land surface, suggesting that paleodrainage patterns during the deposition of these sediments may have been similar to those of the present drainage system. Examination of the results in the context of the available regional geologic control supported the interpretation that deposition of the intermediate silty unit was restricted to the paleodrainage valleys and that this unit is not areally extensive.

Groundwater geochemical (major cations, anions, trace metals) and isotopic (carbon, oxygen, deuterium, and tritium) analyses demonstrated a common origin for groundwater throughout the Bruno aquifer system, as the probable result of fairly local, geologically recent infiltration of precipitation. Subtle variations in the distribution of these parameters suggested, however, that vertical hydraulic communication between the upper and lower sandy zones of the aquifer system might be partially or locally impeded by the intermediate silty unit within the study area. This interpretation was independently corroborated by manual water level measurements made in the network of monitoring wells in the upper and lower sandy zones.

Groundwater levels throughout the aquifer system rose during the monitoring period, as shown for the upper sandy zone in Figure 5. The observed water level trends within each aquifer zone and for the upper and lower wells in each well cluster differed significantly, however, indicating a complex, time-varying pattern of both horizontal and vertical hydraulic gradients across the Bruno site. A transient reversal of the apparent groundwater flow direction in the upper sandy unit and a northwestward shift in the lower sandy zone were observed to correspond with a period of very heavy rainfall, high surface runoff, and rapid groundwater rise near the creek during summer 1994.

Estimates of horizontal hydraulic conductivity (K_h) for the upper and lower sandy units were obtained from the aquifer pumping tests. These results also suggested low vertical hydraulic conductivity (K_v) within the silty unit south and west of the former CCC/USDA facility, with slightly greater K_v toward the north and east.

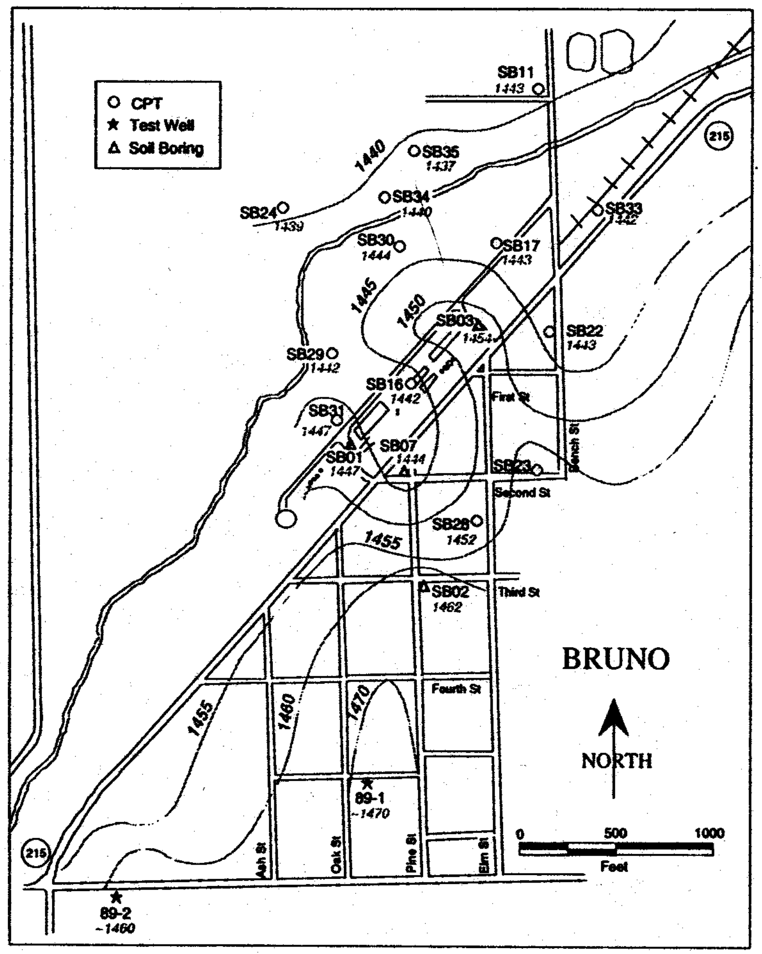

FIGURE 4A Elevation Map (ft AMSL [above mean sea level]) Constructed for the Top Surface of the Upper Sand Zone, Based on Soil Boring and Electronic Cone Penetrometer Data

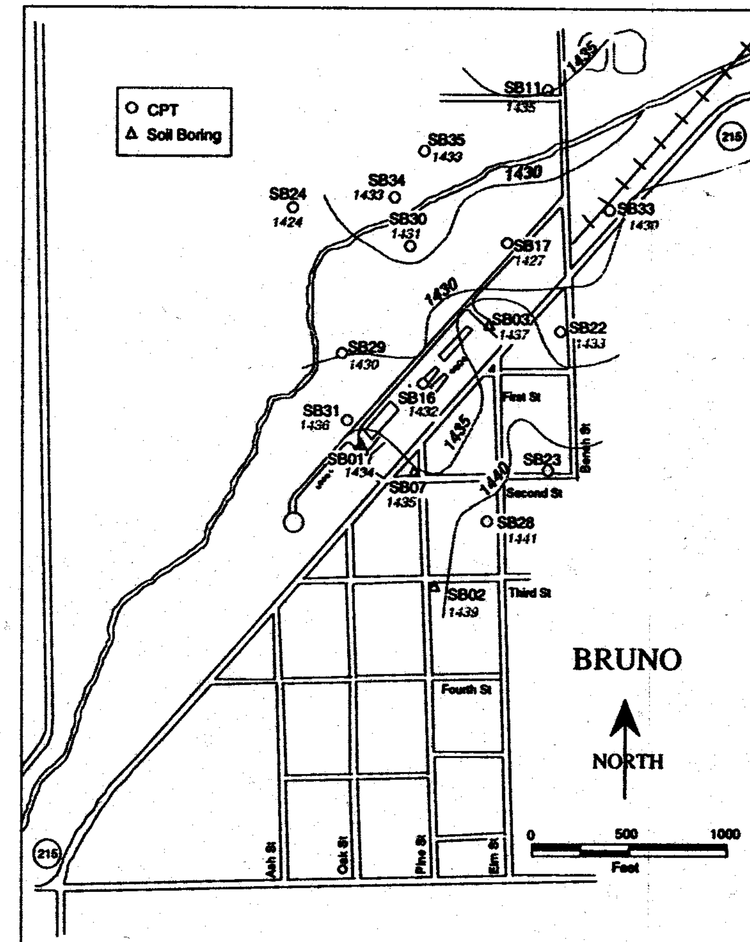

FIGURE 4B Elevation Map (ft AMSL) Constructed for the Top Surface of the Middle Silty Zone, Based on Soil Boring and Electronic Cone Penetrometer Data

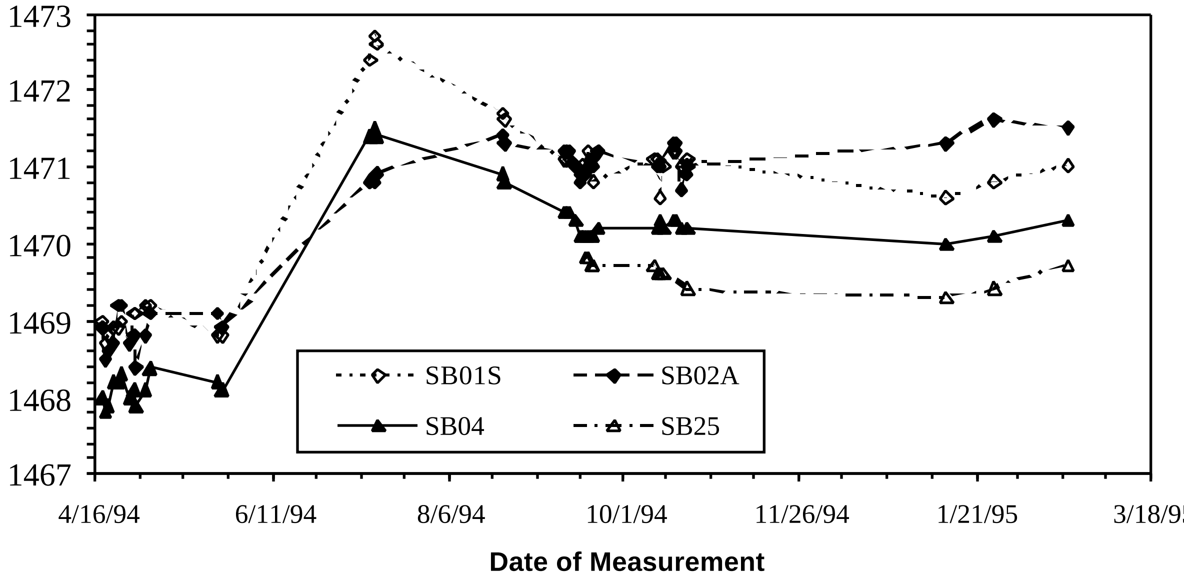

FIGURE 5 Hand-Measured Water Levels for the Upper Sandy Zone, Spanning the Period of Phase I and Phase II Investigations

Groundwater analyses for VOCs revealed a general pattern of carbon tetrachloride distribution within all three zones of the aquifer system (see Figure 6) that was consistent with an apparent net northward to northwestward movement of groundwater; however, this pattern suggested that the vertical and areal distribution of the contamination within the aquifer system was relatively complex.

PRELIMINARY MATHEMATICAL AQUIFER MODELING

The ESC investigations defined a conceptual hydrogeologic model for the Bruno groundwater flow system that built on the preliminary model but added significantly greater complexity. The results suggest that the combined effects of regional recharge to the aquifer system; localized, nonuniform recharge to the upper and lower sandy zones in the low-lying area adjacent to the creek; and inferred variations in the vertical and horizontal hydraulic conductivities of the intermediate silty unit could in large measure account for both the variable groundwater flow patterns and the irregular distribution of carbon tetrachloride contamination observed in the Bruno aquifer system.

To examine this conceptual model, preliminary numerical models of groundwater flow and contaminant transport were constructed and calibrated by using the geologic, hydrologic, and groundwater geochemical constraints obtained from the field investigations. Sensitivity testing of these numerical models indicated that uncertainties in (1) the detailed lithologic and hydraulic characteristics of the intermediate silty unit, (2) the potential for locally preferred groundwater flow and contaminant migration pathways within the aquifer system, and (3) the relative frequency and potential longer-term significance of the seasonal shifts in groundwater flow directions observed at the site limited Argonne’s ability to reliably predict the future

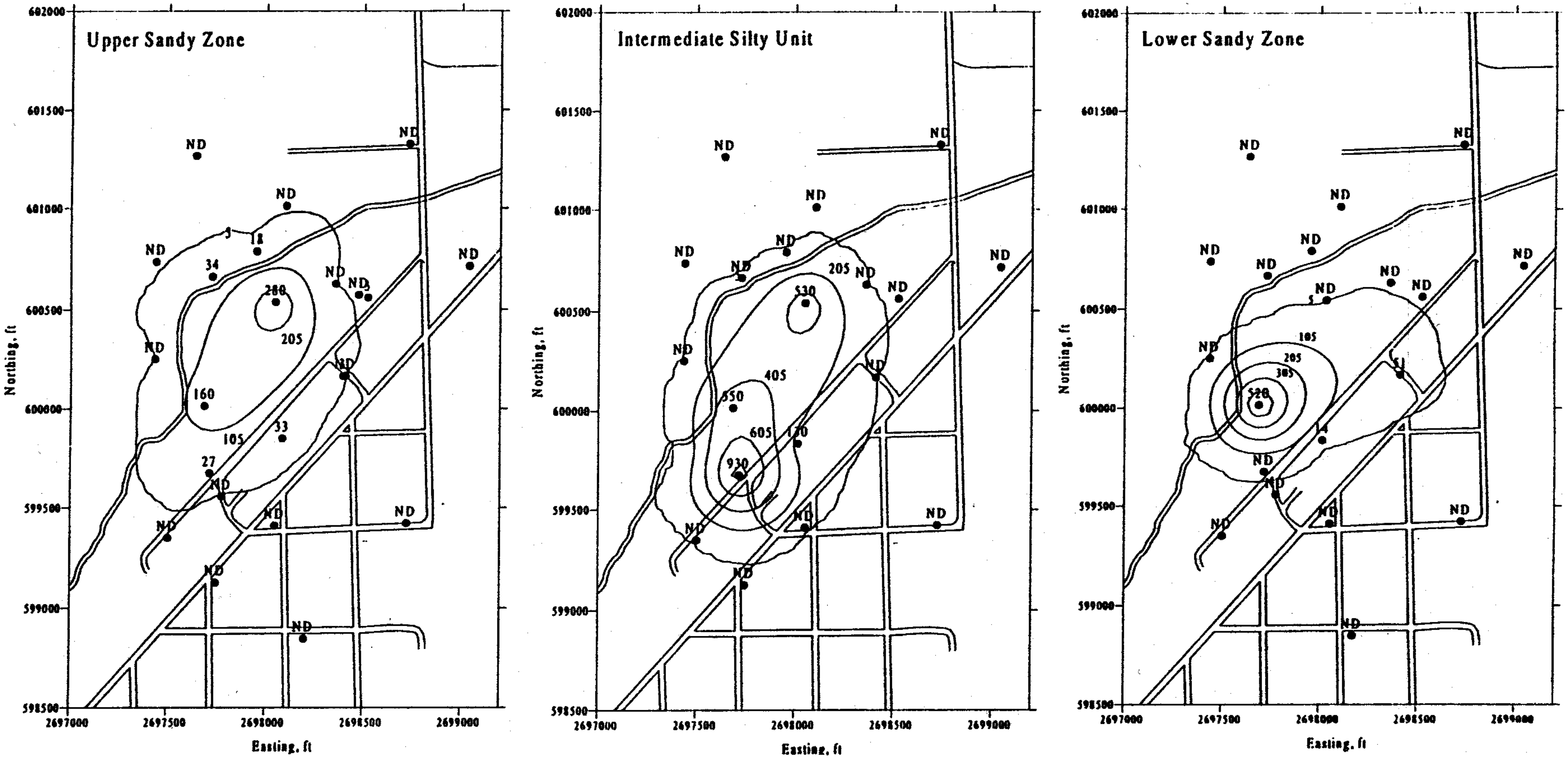

FIGURE 6 Measured Carbon Tetrachloride Concentrations in the Upper Sandy Zone, Intermediate Silty Unit, and Lower Sandy Zone (µg/L)

migration of the carbon tetrachloride contamination within the Bruno aquifer system and hence potential aquifer restoration needs.

EXTENDED MONITORING PROGRAM

On the basis of these conceptual and numerical models, Argonne received regulatory approval to implement an extended program of targeted hydrogeologic monitoring at the site to provide critical data for calibration of the long-term groundwater flow and contaminant transport models necessary for risk analyses. The activities performed under this program included the following:

- Installation of additional temporary monitoring well and piezometer clusters within the upper and lower sandy zones and the intermediate silty unit of the aquifer system at four key locations, to augment the vertical and areal extent of the observation well network established during Phase I and Phase II.

- Continuous recording of water levels within the observation well and piezometer network to determine the responses of the aquifer system to short-term and/or longer-term fluctuations in rainfall and recharge and to possible local pumping activities.

- Quarterly sampling and analysis of groundwater, collected at two temporary monitoring well locations and in adjacent vertical profiles by using the ECPT, to identify the detailed distribution and possible migration pathways of carbon tetrachloride within the aquifer system during the extended monitoring period.

- Targeted soil sampling, analysis of sediment physical properties, and *in situ* hydraulic testing at selected locations to determine the vertical and lateral heterogeneity of the intermediate silty unit.

Argonne proposed that monitoring of groundwater levels and the contaminant distribution within the aquifer system be continued over a period of three to five years, in order to develop a site-specific database reflecting the range of potential annual climatic, rainfall, and water level conditions that might be expected at Bruno. The actual monitoring was conducted over a period of 22 months. In agreement with the regulatory agencies, Argonne considered the hydrogeologic data collected during the Phase I, Phase II, and extended monitoring periods to be acceptable for development of the long-term groundwater flow and transport models to be used in the risk evaluation.

ADDITIONAL CONSTRAINTS ON THE CONCEPTUAL HYDROGEOLOGIC MODEL

The extended groundwater monitoring data confirmed that ambient groundwater flow within both the upper and lower sand units is predominantly to the north or northwest in the vicinity of the former CCC/USDA site, as shown in Figure 7. The ambient hydraulic gradients in these zones are similar in magnitude and appear to remain relatively constant despite observed fluctuations in absolute groundwater levels within the aquifer system associated with seasonal to annual variations in rainfall patterns.

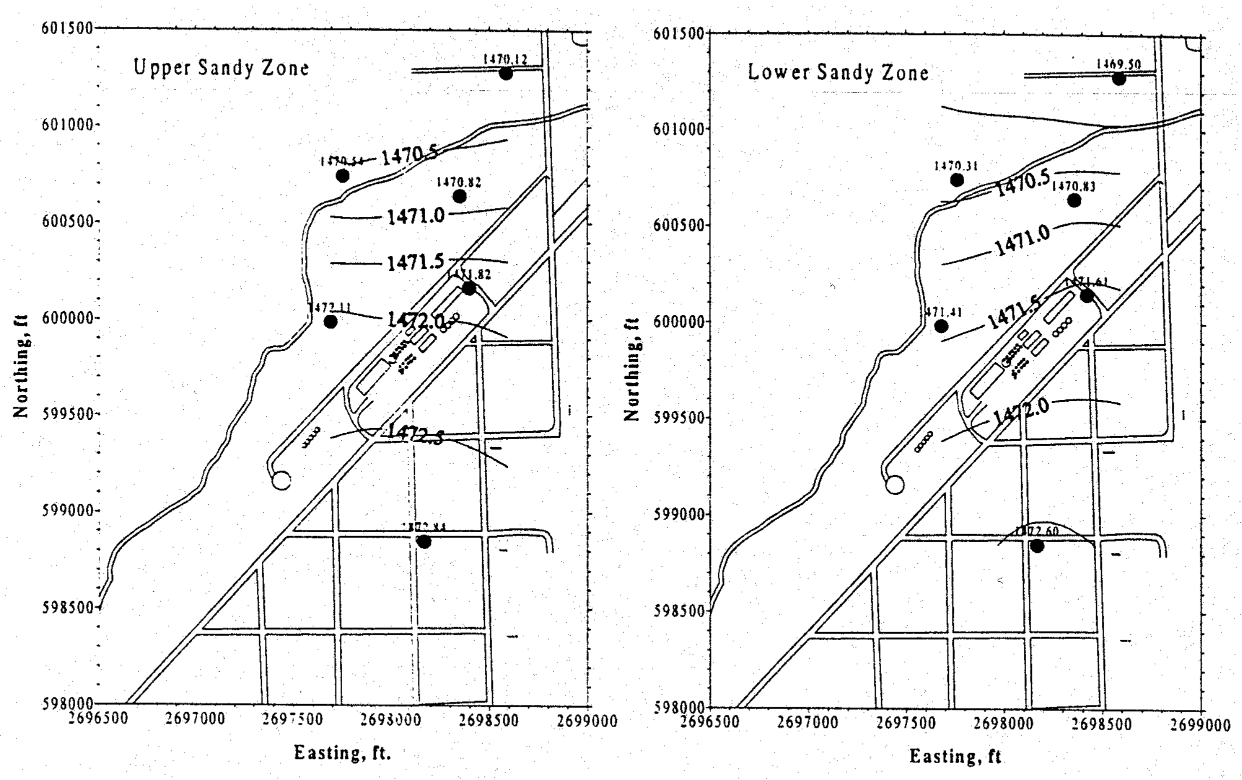

FIGURE 7 Representative Potentiometric Surfaces for the Upper and Lower Sandy Zones under Ambient Hydraulic Gradient Conditions

Locally enhanced recharge to the aquifer system in the immediate vicinity of the former CCC/USDA site resulted in transient groundwater mounding and altered groundwater flow patterns within the upper and lower sandy zones (see Figure 8), as observed in the Phase I and Phase II manual water level measurements, during extended periods (several consecutive months) of consistently heavy, frequent rainfall. The continuous monitoring data demonstrated, however, that these mounding effects occurred in response to individual rainfall/recharge events during such wet periods and were relatively short lived (see Figure 9). An analysis of historic rainfall data available for the Bruno area indicated that the rainfall conditions required to produce transient mounding effects at the site have probably occurred in approximately 75% of the last 40 years.

A fairly sharply defined, thin, silt-clay layer identified at or near the base of the intermediate silty unit in the western and central portion of the Bruno study area pinches out toward the east and northeast across the site. Where it is present, this layer forms the most significant barrier to vertical groundwater and contaminant migration across the silty unit. Groundwater monitoring data demonstrate that the upper sandy zone and the portion of the intermediate silty unit above the silt-clay layer appear to be in direct hydraulic communication with each other; however, the vertical and horizontal hydraulic conductivities of the silty unit are relatively low. The K_h, K_v, and sand content of the silty unit increase in the area northeast of the former CCC/USDA facility. These observations account for the lateral offset in transient mounding effects observed in the upper versus lower sandy zones.

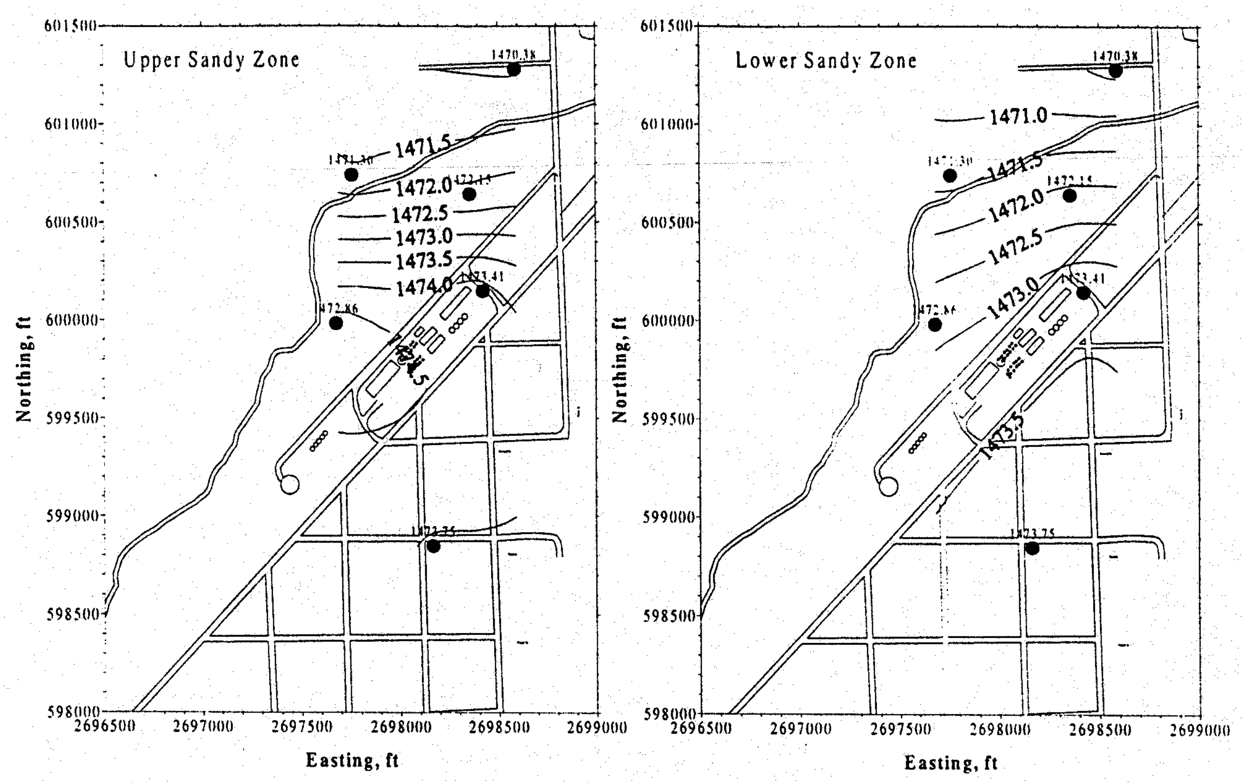

FIGURE 8 Example Potentiometric Surfaces for the Upper and Lower Sandy Zones under High Rainfall/Recharge Conditions

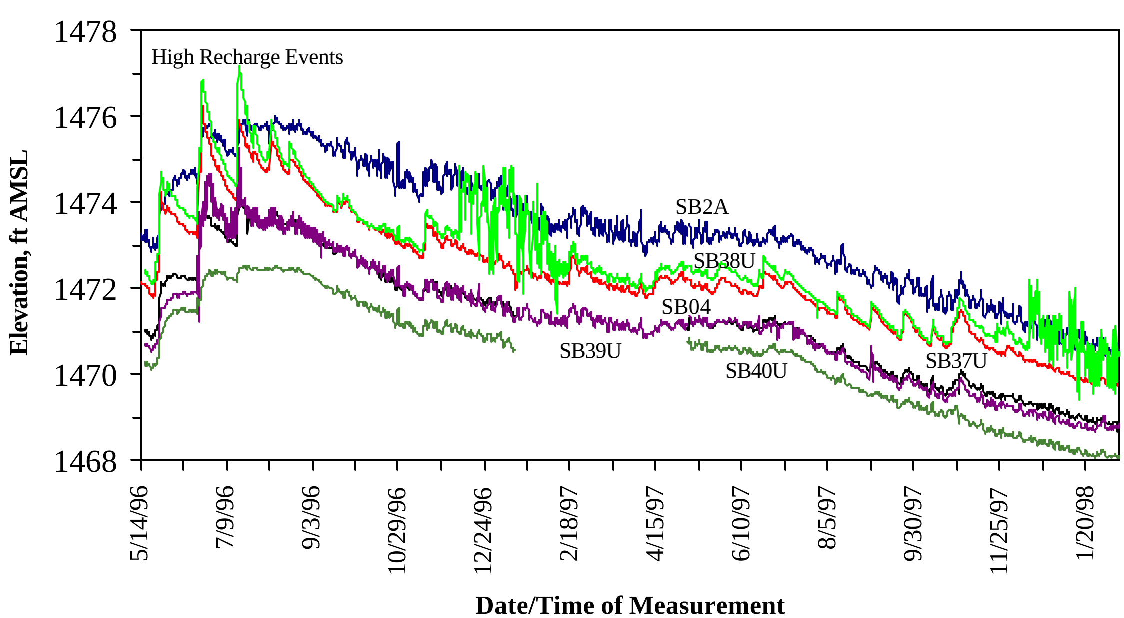

FIGURE 9 Hydrographs for the Upper Sandy Unit, Recorded during the Extended Monitoring Program

Groundwater sampling data during the period of extended monitoring showed no evidence for significant natural contaminant migration within the aquifer system. The periodic sampling demonstrated, however, that groundwater flow to the monitoring wells during sampling (induced by low-rate pumping) preferentially occurred from portions of the aquifer units with higher (relative) carbon tetrachloride concentrations and, by implication, greater (relative) groundwater and contaminant mobility. On the basis of these observations, the maximum carbon tetrachloride levels identified for each location and hydrostratigraphic zone within the aquifer system were considered most representative for use in predicting contaminant migration, as outlined below.

FINAL SITE MODELS AND DYNAMIC RISK ANALYSIS

The construction of final site conceptual and (when necessary) mathematical models requires an understanding of (1) the hydrogeologic processes controlling groundwater flow and contaminant transport and (2) the physiographic and cultural setting of the area under investigation, in order to define a practical and technically defensible basis for the analysis of human health risks. In conducting risk analyses, Argonne employs a dynamic assessment approach under which the health risks posed to actual or hypothetical residents at physically realistic locations within the study area are calculated by using the expected time-versus-concentration profiles associated with migration of the contaminated groundwater at those locations.

The preliminary mathematical models of groundwater flow and contaminant transport were recalibrated by incorporating the additional hydrogeologic constraints on the site conceptual model outlined above. Predictive flow and transport runs were used to simulate the effects on long-term contaminant migration of transient recharge events near the former CCC/USDA site, in keeping with the historic patterns of annual rainfall identified for the area. These simulations ultimately demonstrated that significant downgradient migration of carbon tetrachloride is expected only within the upper and lower sandy zones (see Figure 10); under the identified conditions at the site, the contamination within the intermediate silty unit appeared effectively immobile.

All residents within Bruno receive their domestic water from an uncontaminated municipal supply and are at no risk from the existing groundwater contamination. The area surrounding Bruno, particularly the region downgradient, is very sparsely populated and shows no indications of recent or probable population growth. Agricultural irrigation is uncommon in this area because of the fairly rolling local topography. The regional hydrogeologic studies performed by NWS (Ginsberg 1983) further indicated that the Pleistocene geologic units that host the Bruno aquifer system are absent in the area 2-2.5 mi north and northwest of the village; residents in this area obtain their water from deep Cretaceous aquifers.

On the basis of these observations, Argonne identified fewer than 12 occupied residences north and northwest of Bruno that might rely on private wells within the Pleistocene aquifer system for their sole source of domestic water. Of these, the four residences nearest the anticipated contaminant migration pathway (sites 1-4 in Figure 10) were considered as potential observation points for the calculation of long-term health risks; however, the results of the long-term simulations showed no expected risk at these locations.

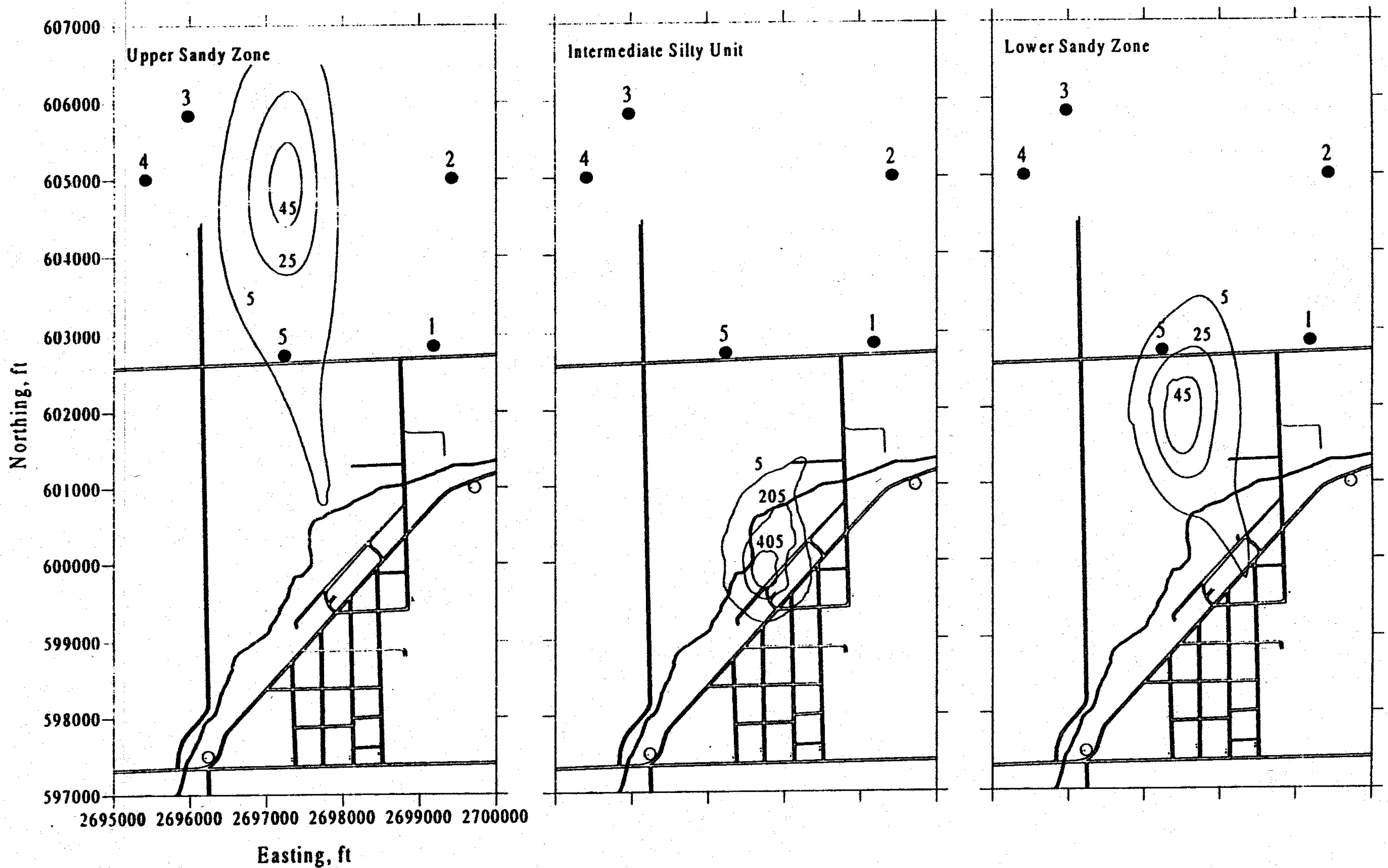

FIGURE 10 Simulated Plume Configurations in the Upper Sandy Zone, Intermediate Silty Unit, and Lower Sandy Zone after 100 Years of Migration (Concentrations are in µg/L.)

For the final Bruno conceptual and mathematical models, a location (site 5 in Figure 10) along the first existing road north of the village was considered as the *nearest reasonable site* for the potential construction of a new residence that might not be served by a connection to the municipal water supply system and that would lie directly within the expected contaminant migration pathway. The location of this hypothetical residence was used as the primary observation point for the calculation of baseline (no-action) health risks associated with the carbon tetrachloride contamination of the Bruno aquifer system.

The dynamic risk analyses indicated that long-term contaminant migration within the upper and lower sandy units only might pose an unacceptable future health risk at the defined observation point, requiring an evaluation of alternative groundwater remediation scenarios. Subsequent remediation feasibility studies for the site employed the calibrated site models and risk-based evaluation procedures outlined above and focused on the reduction of mobile contaminant levels in these zones only.

SUMMARY

The systematic development and critical evaluation of an integrated, process-oriented, conceptual hydrogeologic model is an essential element in the expedited characterization of hazardous waste sites. The conceptual model provides a framework for the selection of appropriate characterization techniques, for the integration and interpretation of site data, and for the identification of critical data needs. The Bruno example demonstrates that the effective construction of site conceptual and (when necessary) mathematical models, incorporating an understanding of both the hydrogeologic processes controlling groundwater flow and contaminant transport and the physiographic and cultural characteristics of the area under investigation, also provides the practical and technically defensible basis necessary for the analysis of human health risks with Argonne’s dynamic risk assessment approach.

ACKNOWLEDGMENT

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